

PARTITIONING TUNGSTEN BETWEEN MATRIX PRECURSORS AND CHONDRULE PRECURSORS THROUGH RELATIVE SETTLING

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ABSTRACT

Recent studies of chondrites have found a tungsten isotopic anomaly between chondrules and matrix. Given the refractory nature of tungsten, this implies that W was carried into the solar nebula by at least two distinct families of pre-solar grains. The observed chondrule/matrix split requires that the distinct families were kept separate during the dust coagulation process, and that the two families of grain interacted with the chondrule formation mechanism differently. We take the co-existence of different families of solids in the same general orbital region at the chondrule-precursor size as given, and explore the requirements for them to have interacted with the chondrule formation process at significantly different rates. We show that this sorting of families of solids into chondrule and matrix destined dust had to have been at least as powerful a sorting mechanism as the relative settling of aerodynamically distinct grains at at least two scale heights above the midplane. The requirement that the chondrule formation mechanism was correlated in some fashion with a dust grain sorting mechanism argues strongly for spatially localized chondrule formation mechanisms such as turbulent dissipation in non-thermally ionized disk surface layers, and argues against volume filling mechanisms such as planetesimal bow shocks.

Subject headings: hydrodynamics—solid state: refractory—meteorites—protoplanetary disks—planets and satellites: composition

1. INTRODUCTION

Chondrites are a class of relatively unprocessed undifferentiated meteorites which inform us about the components from which, and the environment in which, they were assembled. They are named after chondrules, sub-mm inclusions which were melted at temperatures above 1700 K (Hewins 1997), and which contribute a significant mass and volume fraction of their hosts. The other major constituent of chondrites is fine-grained matrix, which was never melted and mostly remained cold (Huss et al. 2003). Interestingly, the elemental composition of matrix and chondrules are different, even within a given chondrite (Ebel et al. 2016). This is significant because particles the size of chondrules were presumably agglomerations of sub-micron interstellar dust grains (Draine 2003). Any scatter in the composition of the sub-micron grains should have been washed out once averaged by the billion. Even in the case of very rare elements, which might have been carried by only a handful of initial grains, a handful of initial grains among billions could not have determined whether their host agglomeration went on to be melted into a chondrule or not.

The chondrule heating process itself surely explains some of the moderately volatile abundance differences between chondrules and matrix (Hewins 1991; Hubbard 2016b). However, compositional differences have also been found for quite refractory species including Ca, Al and Ti (Ebel et al. 2016). Further, Budde et al. (2015) found isotopic differences between highly refractory tungsten found in Allende’s chondrules compared to its matrix. Those differences are not due to hafnium decay but instead are well fit by differing abundances of r- and s-process nucleosynthesis products. It is difficult to imagine how thermal or chemical processing during chondrule formation could have generated such isotopic

heterogeneities in such a refractory species. This suggests that the elemental and isotopic compositions of chondrule-precursors differed from those of matrix-precursors, and that they differed for reasons beyond thermal or chemical processing.

This puzzle is exacerbated by the fact that protoplanetary disks, of which the solar nebula has no reason to have been an exceptional example, are expected to be vigorously turbulent and well mixed (Goldberg et al. 2015). That means that any compositional gradients in the solar nebula had to have been shallow, and it would have taken long time scales for the accretion flow through the disk to have brought in gas-dust mixtures with meaningfully different abundances. Chondrules are small and extremely well coupled to the gas (Jacquet et al. 2012; Hubbard & Ebel 2015). Accordingly, even if there was a large scale isotopic gradient in the disk, nearly all the chondrules formed at one location would have been carried away by turbulent diffusion or the accretion flow itself by the time sufficient accretion had occurred for the local abundances to have changed.

It has also been found that different chondrite classes, with very different chondrule to matrix ratios, and matrix and chondrules with significantly different abundances, nonetheless have similar bulk abundances in a phenomenon known as complementarity (Hezel & Palme 2010). This makes invoking large scale abundance gradients to explain the differences between chondrules and matrix abundances even less plausible: if chondrules and matrix were formed from solids contained within different volumes of gas, and had very different abundances, then how could they have been subsequently combined in the correct (but wildly varying) ratios for their bulk abundances to approximate chondritic? Indeed, Goldberg et al. (2015) showed that complementarity cannot then be maintained for prolonged time scales, and that matrix and chondrules must have been in some fashion co-genetic.

The implications of complementarity, and how strong the

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relationship between matrix and chondrules is, is not yet fully certain. Bulk compositions of chondrites certainly vary at the ten percent level (Hezel & Palme 2010). It is also clear that different chondrite classes drew from separate reservoirs within the solar nebula; and it seems likely that different chondrites within a given class did so as well (Jones 2012). Refractory titanium carries an isotopic signature which shows modest scatter between chondrite classes (Trinquier et al. 2009). Nonetheless, complementarity seems to be a particularly strong hypothesis for tungsten isotopes, with Allende’s bulk composition falling neatly in line with the rest of the inner solar system’s (Budde et al. 2016).

2. MOTIVATION

How could chondrules and matrix have ended up with differing isotopic signatures in highly refractory elements as has been found experimentally for tungsten? The highly refractory nature of tungsten, and the nucleosynthetic nature of the W isotopic signature both imply that the signal cannot be due to either thermal or chemical processing in the solar nebula, or due to hafnium decay. This is particularly important because the chondrule formation process involves extreme temperatures and conditions (Hewins 1997). Because it did not originate in the solar nebula, it must have been carried into the solar nebula by pre-solar grains of differing origins. For us to see a pre-solar grain based isotopic signature between different chondritic meteorite components, the different, submicron-scale pre-solar grains had to have experienced the collisional dust growth process differently. If they didn’t, then averaging over billions of pre-solar grains would have washed out any isotopic signal.

One way to achieve this would be if the grains were found in different regions, or were injected into the disk at different times, when differing dust dynamics dominated. This would also allow an easy explanation of the different fates of the grains: chondrule formation temporal or spatial intermittency, and matches well with the observations that chondrules in different chondrite classes, and even within the same chondrite class, were drawn from different reservoirs within the solar nebula (Jones 2012). Those reservoirs even differed in refractory isotopes (e.g. titanium, Trinquier et al. 2009). However, the separation of tungsten isotopes between chondrules and matrix seen Allende is extremely large compared to variations in the bulk tungsten isotope ratios of inner solar system bodies, including itself (Budde et al. 2016). Thus, Allende is tungsten-isotope-complementary with the inner solar system. Therefore, spatial or temporal differences in the pre-solar grain injection violates complementarity: as found by Goldberg et al. (2015), for matrix and chondrules to have had correlated composition, they had to have been co-genetic.

Because of the complementarity constraints, the two dust grain categories with different W isotopic signatures had to have spatially and temporally overlapped. Any other solution would need to explain why Allende has exactly the correct chondrule volume fraction to match the inner solar system’s tungsten isotope ratios, while chondrites as a class have strongly varying chondrule volume fractions. This requires two separate effects. Firstly, the W isotopes had to have been split between two categories of dust agglomerations. Henceforth we will use “dust” to refer to solids in general, and “dust grain” for individual objects. Secondly, those two categories had to have been destined to different, chondrule or matrix, fates. We leave the details of partitioning elements and isotopes between different families of dust grains to a companion

paper (Hubbard 2016a, hereafter Paper I) and focus here on the different destinies of the families.

If chondrule heating events occurred sporadically but reasonably spatially evenly across broad reaches of the solar nebula then they should have hit regions which selected for all types of dust compositions. If, however, chondrule forming events were highly spatially localized, then differences in dust particle aerodynamics, which would have allowed for spatial separation of agglomerations of differing compositions on small enough scales to not disrupt complementarity (Takeuchi & Lin 2002), would have also allowed for the creation of the W isotope signature. As a hypothetical scenario with spatially localized chondrule melting we focus on vertical settling, assuming that chondrule forming events occurred primarily high above the disk midplane: more settled dust agglomerations would have been less likely to have been melted. Many elements are partitioned between matrix and chondrules (Ebel et al. 2016); and the process we will develop would not only explain W isotopic signatures, but would drive variations in any abundances which were correlated with the dust aerodynamical properties. We focus on the tungsten isotopic signature only because it is nearly invulnerable to thermal and chemical processing.

Tungsten is extremely rare (about 10^{-7} by mass, Lodders 2003) so cannot have caused any difference in the dust fate by itself. Instead, W must trace a more significant difference between the dust families. In Paper I we noted that iron is also partitioned between chondrules and matrix. It is easy to imagine that different tungsten isotopes, created in different nucleosynthetic environments, would have been found in pre-solar grains of differing iron metal abundances. This led us to propose that ferromagnetic interactions between dust grains (Harris 1967) both helped preserve primordial inhomogeneities, and also allowed the different dust families to grow to different sizes, with different aerodynamics.

Even though Fe is strongly partitioned between matrix and chondrules, which inspired Paper I, that partitioning is certainly at least in part due to thermal and chemical processes, e.g. during the extreme conditions of chondrule formation itself (e.g. Campbell et al. 2005). However, iron’s ferromagnetism depends on many parameters, so while W isotopes might have been correlated with ferromagnetically active iron, they need not have been correlated with bulk (metallic and non-metallic) iron. Further, because the isotopic signature must have been pre-solar in origin, any other elemental or isotopic signatures implied by any model for the W isotope partitioning would be nucleosynthetic, rather than chemical (i.e. sideophile) in origin unless the model also invokes chemical processing.

While radial pressure perturbations, such as those associated with zonal flows (Johansen et al. 2009), can also sort dust agglomerations by size, settling is particularly attractive because the vertical structure of disks has the same lifetime as the disk itself, avoiding requiring temporal correlations between chondrule formation and dust spatial sorting. Also, the solar nebula’s surface layers are expected to have been more magnetic active due to X-ray and FUV ionization (Gammie 1996), so magnetized turbulent dissipation models for chondrule formation can be plausibly vertically localized. As a final note, restricting chondrule formation to having occurred at altitude would help explain why chondrules are so small (Hubbard & Ebel 2015). Interestingly, altitude restrictions would strongly constrain chondrule formation processes. For example, planetesimal bow shocks (Hood 1998; Morris et al.

2012) can only be produced by populations of highly eccentric planetesimals, whose orbits would presumably also often be highly inclined. Accordingly, if it turns out that chondrule formation was indeed altitude restricted, we can rule out planetesimal bow shocks as the dominant chondrule formation process.

3. DUST VERTICAL DISTRIBUTION

If chondrule formation occurred only above a critical height z_c , then only fraction of the dust vertically mixed above that height would have been melted to make chondrules. Here we calculate the vertical distribution of dust in a vertically isothermal disk in hydrostatic equilibrium following Takeuchi & Lin (2002). A particle moving through gas feels a drag acceleration:

$$\left. \frac{\partial \mathbf{v}}{\partial t} \right|_{\text{drag}} = -\frac{\mathbf{u} - \mathbf{v}}{\tau}, \quad (1)$$

where \mathbf{v} is the particle's velocity, \mathbf{u} the gas velocity at the particle's position and τ is a drag time scale. Dust particles smaller than the local gas mean-free-path (which includes chondrules and their precursors) experience Epstein drag regime, with corresponding drag times:

$$\tau_E = \sqrt{\frac{\pi}{8}} \frac{a \rho_s}{\rho_g v_{th}}, \quad (2)$$

where a are the particles' radii, ρ_s their solid density, ρ_g the local gas density, and

$$v_{th} = \sqrt{\frac{k_B T}{m_m}} \quad (3)$$

the gas thermal speed and m_m the gas molecular mass. Vertically isothermal disks in hydrostatic equilibrium have

$$\rho_g(z) = \rho_{g0} e^{-z^2/2H^2} \quad (4)$$

where ρ_{g0} is the midplane gas density, z is the height above the midplane, Ω_K is the local Keplerian frequency and $H \equiv v_{th}/\Omega_K$ the local gas pressure height.

In the case of protoplanetary disks it is customary to define a Stokes number

$$\text{St} \equiv \tau \Omega_K, \quad (5)$$

where Ω_K is the local Keplerian frequency. This Stokes number describes the degree to which the dust particle can slip through the gas on orbital time scales, which are also expected to be turbulent time scales. Combining Equations (2),(4) and (5) we find

$$\text{St} = \text{St}_0 e^{+z^2/2H^2} \quad (6)$$

where

$$\text{St}_0 = \frac{\pi a \rho_s}{2 \Sigma_g} \quad (7)$$

is the Stokes number at the midplane. For scale, at $R = 2.5$ AU in an MMSN (Hayashi 1981), an $a = 0.25$ mm, $\rho = 3 \text{ g cm}^{-3}$ chondrule would have had $\text{St}_0 \lesssim 3 \times 10^{-4}$. Chondrule precursors, being porous, would have had significantly lower midplane Stokes numbers. As we next develop, this value for St_0 is low enough that we expect strong vertical mixing in any scenario which includes sufficiently vigorous surface layer turbulence to drive chondrule formation (Oishi et al. 2007).

To lowest order in z , where z is the height above the midplane, the vertical force of gravity in a protoplanetary disk is

$$g_z = -z \Omega_K^2. \quad (8)$$

The small value of St_0 estimated above implies that chondrule and chondrule-precursor sized agglomerations were well enough coupled to the gas that they can be assumed to have reached terminal velocity, with

$$v_z = -z \Omega_K^2 \tau = -\text{St} \frac{z}{H} v_{th}, \quad (9)$$

which drives a dust settling flux of

$$F_S = v_z \rho = -\text{St} \frac{z}{H} \rho v_{th}, \quad (10)$$

where ρ is the dust fluid density.

Protoplanetary disks are expected to be turbulent, with a corresponding turbulent diffusivity for the dust \mathcal{D} which we scale through a parameter β :

$$\mathcal{D} \equiv \beta v_{th} H, \quad (11)$$

Note that our β is approximately, but not identically, the α of an α -disk (Shakura & Sunyaev 1973), and the details of how turbulence drives or is driven by angular momentum transport, and any anisotropy in the turbulence, could reasonably lead to α and β differing by factors of a few. Turbulent diffusion drives a diffusive vertical dust flux

$$F_D = -\rho_g \mathcal{D} \partial_z \left(\frac{\rho}{\rho_g} \right), \quad (12)$$

where ρ_g is the gas density. A vertical steady state is reached when the total vertical flux is zero:

$$F = F_S + F_D = 0. \quad (13)$$

Combining Equations (6), (10), (12) and (13), we finally arrive at:

$$\rho(z) = \rho(0) \exp \left[-\frac{z^2}{2H^2} - \frac{\text{St}_0}{\beta} \left(\exp \frac{z^2}{2H^2} - 1 \right) \right]. \quad (14)$$

The dust midplane density $\rho(0)$ can be found in terms of the dust surface density Σ_d by using

$$\Sigma_d \equiv \int_{-\infty}^{\infty} dz \rho(z). \quad (15)$$

Note that in the derivation of Equation (14) we have assumed that β is a function neither of z nor of St . Equation (14) implies that the settling criteria is

$$\frac{\text{St}}{\beta} = \frac{\text{St}_0}{\beta} \exp \frac{z^2}{2H^2} \gtrsim 1, \quad (16)$$

We expect $\beta \sim \alpha \ll 1$, so dust should be extremely settled well below heights at which $\text{St} \sim 1$. Accordingly, only regions with $\text{St} \ll 1$ contribute, and the assumption that β is not a function of St is well founded (Youdin & Lithwick 2007). We are explicitly assuming that chondrule formation events are correlated with height, and the dissipation of magnetized turbulence is an obvious possible explanation for that: poorly ionized midplanes are not expected to be strongly turbulent (Gammie 1996). In this scenario β would be expected to vary with altitude. However, the value of β does not matter in determining $\rho_d(z)$ as long as $\text{St}/\beta \ll 1$. Our approximation of

β being independent of z therefore extends to

$$\frac{St(z)}{\beta(z)} \ll 1 \quad (17)$$

anywhere in the vertical column below the chondrule formation height, i.e. for all $|z| \ll z_c$.

If there was a sufficiently thick and dead midplane dead-zone, then Equation (17) would not be satisfied, and all the potential chondrule precursors would settle into a very thin layer at the midplane. This is unlikely, as the low micro-physical hydrodynamical viscosity (as opposed to a turbulent effective viscosity) of protoplanetary disks means that any turbulent stirring in the surface layers would penetrate to the midplane with strength sufficient to mix $St_0 \sim 10^{-4}$ particles (Oishi et al. 2007). As we will show in Figure 1, large aerodynamical variations between dust families could still drive relative settling in the extremely low turbulence case; but it is hard to see how any chondrule melting processes active in such a laminar region of the disk, such as planetesimal bow shocks, would treat different altitudes differently. Accordingly, we retain the assumption that Equation (17) is satisfied, which places qualitative lower bounds on α and β . We emphasize that the strong height dependence of St (Equations 6), along with the small St of chondrules, and the even smaller St of their porous precursors, nonetheless allows for even quite deadish dead zones.

4. CHONDRULE MELTING FRACTIONS

We assume the existence of two compositionally distinct dust agglomeration populations in the solar nebula whose aerodynamics were different, with midplane Stokes numbers $St_1 < St_2$. In future studies of chondrule and matrix abundances, the aerodynamical difference would be due to how the compositional variation affected the coagulation processes, so the ratio St_2/St_1 would be a known constraint. We also assume that chondrule melting events only occurred above a critical height z_c . We can use the vertical dust distributions calculated above to determine the fraction of the dust populations which were above z_c , and hence the different rates at which the two populations were converted into chondrules.

From Equations (14) and (15) the fraction of dust population i which is found in the chondrule forming region is

$$f_i = \frac{2 \int_{z_c}^{\infty} dz \exp \left[-\frac{z^2}{2H^2} - \frac{St_i}{\beta} \left(\exp \frac{z^2}{2H^2} - 1 \right) \right]}{\int_{-\infty}^{\infty} dz \exp \left[-\frac{z^2}{2H^2} - \frac{St_i}{\beta} \left(\exp \frac{z^2}{2H^2} - 1 \right) \right]}, \quad (18)$$

where the factor of 2 accounts for the upper and low halves of the disk, assumed to be symmetric about the midplane. The ratio between the fractional rates at which the two dust populations are processed to make chondrules is given by

$$\xi \equiv f_2/f_1, \quad (19)$$

which is a function of St_2/St_1 , St_2/β and z_c/H (or other permutations). Note that, as we have arbitrarily set $St_1 < St_2$, we expect $\xi < 1$: the dust grain population $i = 2$, made of larger, more settled grains, would have preferentially settled out of the chondrule forming region.

Considerations of how much matrix was thermally processed suggest that only a small fraction of ambient dust was ever processed into chondrules (Hubbard & Ebel 2015). As long as that was indeed the case, the ratio of the rates at which the dust populations were melted to make chondrules was also the ratio of the mass fractions of the populations which were

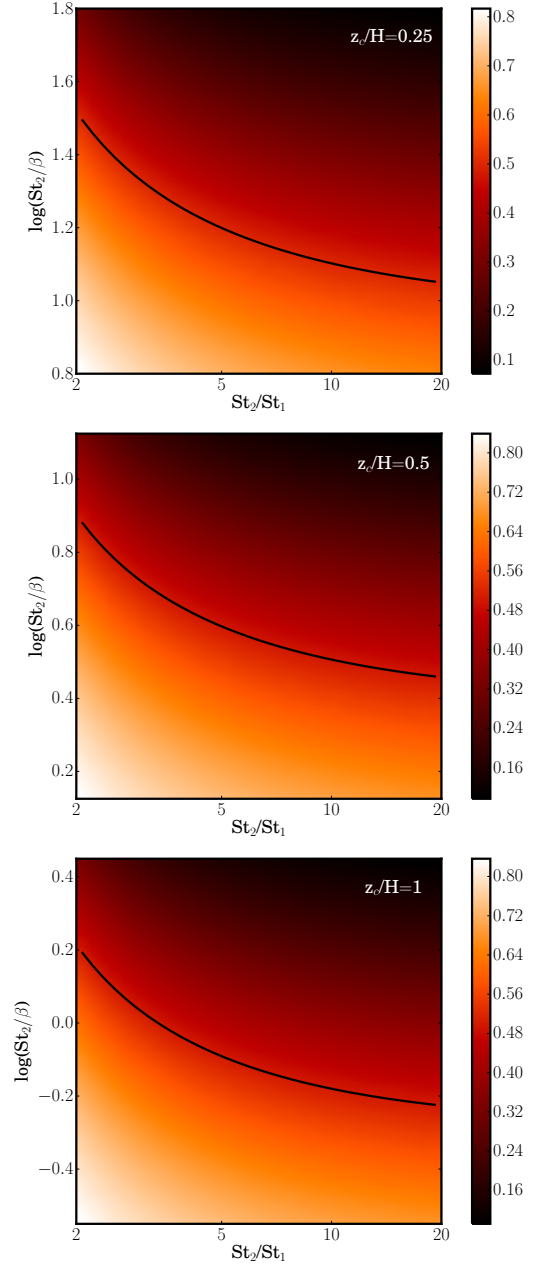


Figure 1. Chondrule processing ratio ξ (Equation 19) as a function of St_2/St_1 and St_2/β for $z_c/H = 0.25, 0.5, 1$. Contour is 0.5. Note that the x-axis is logarithmic.

melted into chondrules. Using that assumption we can explore the consequences of ξ . We assume that population 2 contained a fraction f of the total dust mass, and population 1 contained the rest (i.e. a fraction $1 - f$). We also assume that population i contained a mass fraction g_i of a given element or isotope of interest. Then the overall mass fraction of that element was simply

$$g_1(1 - f) + g_2f, \quad (20)$$

while the chondrule mass fraction of that element would have been

$$\frac{g_1(1 - f) + \xi g_2f}{(1 - f) + \xi f}, \quad (21)$$

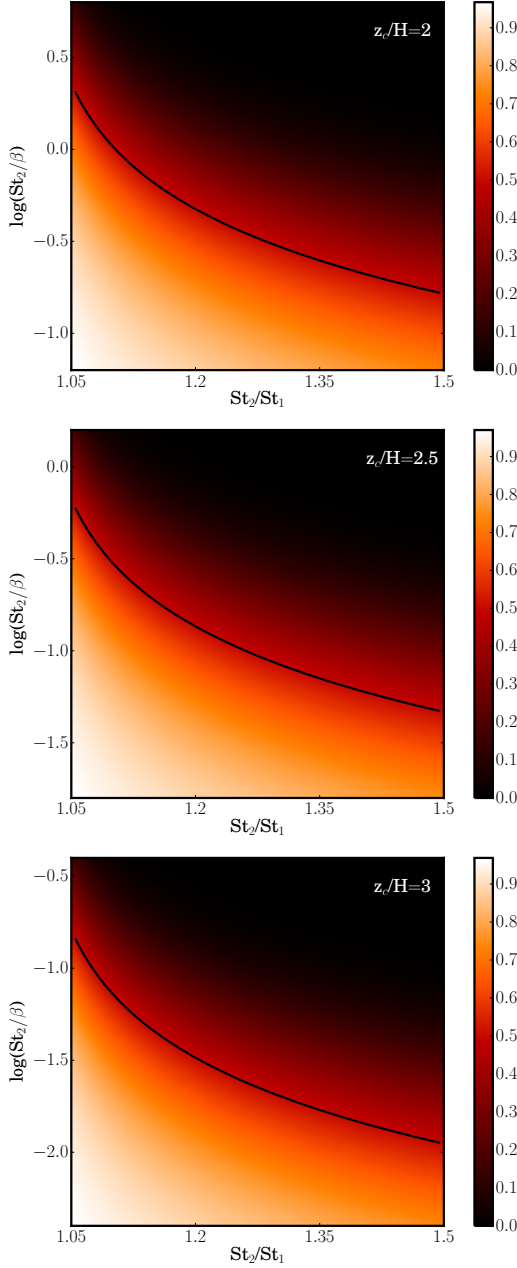


Figure 2. Chondrule processing ratio ξ (Equation 19) as a function of St_2/St_1 and St_2/β for $z_c/H = 2, 2.5, 3$. Contour is 0.5. Note that the x-axis is linear.

and the enrichment factor EF of that element compared to bulk ambient dust (which is not the same as future chondrite bulk) would have been

$$EF = [g_1(1-f) + g_2f]^{-1} \frac{g_1(1-f) + \xi g_2f}{(1-f) + \xi f}. \quad (22)$$

Note that depletion is represented by $EF < 1$. In the limiting case of $g_2 = 0$ we find that the enrichment factor would have been

$$EF = \frac{1}{(1-f) + \xi f} > 1, \quad (23)$$

which tends to ξ^{-1} as f tends to 1. On the other hand, in the

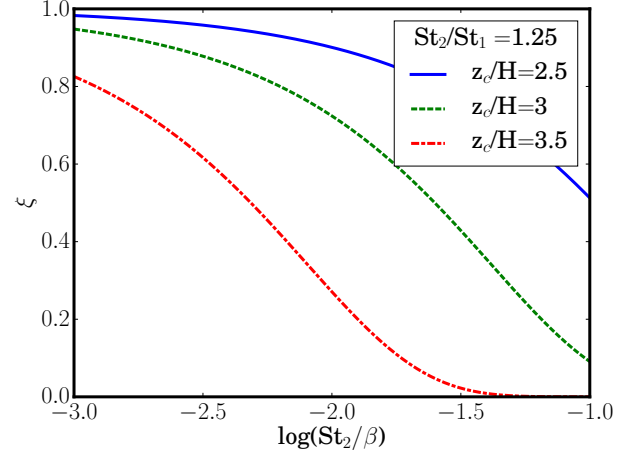


Figure 3. Chondrule processing ratio ξ (Equation 19) as a function of St_2/β for $St_2/St_1 = 1.25$ and three different values of z_c/H . Blue/solid: $z_c/H = 2.5$, green/dashed: $z_c/H = 3$, red/dash-dotted: $z_c/H = 3.5$.

limiting case of $g_1 = 0$ we have depletion, with

$$EF = \frac{\xi}{(1-f) + \xi f} < 1, \quad (24)$$

which tends to ξ as f tends to 0. If all of our element of interest was found in dust grains that were preferentially melted to make chondrules/preferentially preserved as matrix, then a significant enrichment/depletion of that element in chondrules with respect to bulk was possible.

In Figures (1) and (2) we plot the ratio ξ for a variety of parameters. The contours show the line $\xi = 0.5$, at which value twice the fraction of the smaller (lower St) of the two dust agglomerations populations would have been processed into chondrules compared to the larger dust agglomeration population. As sketched above, even in the limit of extreme dust elemental or isotopic inhomogeneities, $\xi < 0.5$ is required for order-unity enrichment or depletion of chondrules with respect to the overall bulk abundances. As such, $\xi = 0.5$ can be taken as an upper limit for values of ξ which could explain compositional variations between chondrules and matrix. Disk surface layers are expected to be strongly turbulent, and must have been for turbulent dissipation to be the chondrule melting mechanism. Accordingly, we can use

$$\beta \sim \alpha \gtrsim 10^{-3} \quad (25)$$

as a generous lower bound on β . As calculated in Section 3, chondrule midplane Stokes numbers were approximately $St_0 \simeq 3 \times 10^{-4}$, so we can estimate that porous chondrule precursors had $St_0 < 10^{-4}$ (i.e. volume filling fractions below 20%). It follows that we expect $St_0/\beta < 0.1$. Even for extreme values of St_2/St_1 this forces the constraint that $z_c > H$, as can be seen in Figure 1.

Turbulently stirred dust collides at speeds (Voelk et al. 1980)

$$v_c \sim \sqrt{\beta St_c}. \quad (26)$$

For chondrule precursors at the midplane, with $St_0 = 10^{-4}$, and midplane $\beta = 10^{-4}$ in an MMSN at $R = 2.5$ AU with $c_s \simeq 8 \times 10^4$ cm s $^{-1}$, Equation (26) implies $v_c \simeq 8$ cm s $^{-1}$. This lies well between the bouncing and fragmentation barriers (Zsom et al. 2010), so we expect chondrule precursors

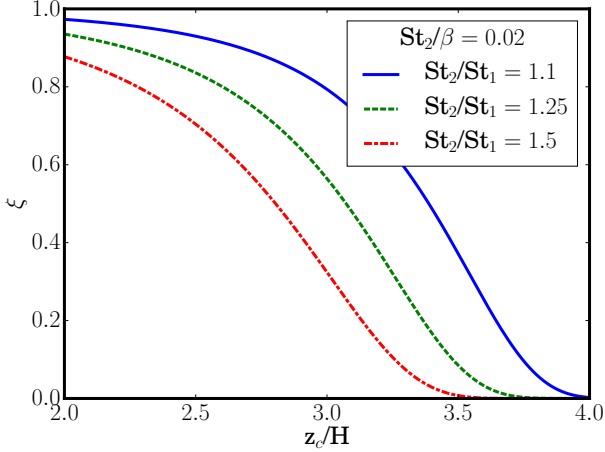


Figure 4. Chondrule processing ratio ξ (Equation 19) as a function of z_c/H for $St_2/\beta = 0.02$ and three different Stokes ratios. Blue/solid: $St_2/St_1 = 1.1$, green/dashed: $St_2/St_1 = 1.25$, red/dash-dotted: $St_2/St_1 = 1.5$.

to mostly bounce upon collision, and to be at an equilibrium between infrequent low velocity sticking events and infrequent high velocity fragmentation events pulled from a nearly Maxwellian turbulent collisional velocity distribution.

In Paper I we noted that the fragmentation rate is controlled by the tail of the turbulent collisional Maxwellian distribution, and hence is an exquisitely sensitive function of the collisional velocity scale. As a consequence, the equilibrium dust size is relatively insensitive to the stickiness of the participants. If that is indeed the controlling factor for the dust size, then we expect $St_2 \sim St_1$. In Figure 2 we can see values of $\xi < 0.5$ can indeed be achieved for $St_2/St_1 < 1.5$ and $St_0/\beta < 0.1$, but only for $z_c > 2H$, and even that altitude is generally insufficient as can be seen in Figure 3. Further, at those altitudes, small changes in z_c/H can have large implications for ξ , as shown in Figure 4.

5. DISCUSSION AND CONCLUSIONS

The partitioning of refractory elements and their isotopes between chondrules and matrix in chondritic meteorites implies that there were elementally and isotopically distinct dust populations, some of which were preferentially melted to make chondrules. This requires not only that dust collisional coagulation cannot have treated all potential collisional partners the same, but also requires that there have existed a mechanism which sorted dust grains into chondrule-precursors and matrix-precursors. If dust collisional coagulation treated potential collisional partners differently, then dust grains with different compositions would be expected to have grown to (slightly) different sizes and hence aerodynamics. We discuss this part of the problem in a companion paper (Hubbard 2016a).

Such a difference in aerodynamics would have allowed the chondrule-or-matrix fate of a dust grain to have been determined through aerodynamical sorting: different dust agglomerations would have been preferentially found in differing regions of the disk. In that case, chondrule formation that was spatially localized in a fashion correlated with the spatial dust sorting would explain how refractory elements were partitioned between matrix and chondrules. If, as seems likely, chemical and thermal processing cannot explain the tungsten

isotope partitioning seen by Budde et al. (2015), then the alternative to dust sorting are large scale solar nebula composition gradients. However, Goldberg et al. (2015) showed that matrix and chondrules had to have been in some fashion co-genetic, which means tapping into a large scale gradient would require extreme fine tuning.

This is particularly pressing for Allende because that meteorite is tungsten-isotopic-complementary with the inner solar system, while its individual components vary strongly (Budde et al. 2016). Given the large chondrite to chondrite matrix volume fractions, it is difficult to imagine why Allende’s chondrules and Allende’s matrix would have originated from separate, unmixed dust reservoirs within the solar nebula, and yet still have been subsequently mixed in exactly the correct ratio to produce the observed uniform inner solar system bulk compositions.

While tungsten is highly refractory, some of the compositional variation between matrix and chondrules is undoubtedly due to partitioning of more volatile elements during chondrule melting by evaporation (for a selection of matrix/chondrule compositional differences, see Ebel et al. 2016). Further, because chondrules and matrix likely had differing aerodynamics, they were likely consumed by the parent body formation process at differing rates (Hubbard & Ebel 2015). This means that even if ambient proto-matrix and chondrules were perfectly correlated in the solar nebula, they would be imperfectly correlated, especially in the more volatile elements, once combined into a parent body. Because isotopic signatures in general, and highly refractory tungsten isotopes specifically are relatively unaffected by thermal or chemical processes, they offer an excellent complement to the partitioning of more volatile elements in learning how correlated the matrix and chondrules actually were, and especially how that correlation came to be or was maintained.

We have examined the conditions required for dust spatial sorting and chondrule forming localization to generate significant partitioning. We found that partitioning is possible, but requires strong sorting comparable to settling at high, $z > 2H$, altitude, and more likely regions of parameter space require $z \gtrsim 3H$. This argues strongly against vertically stochastic chondrule forming mechanisms such as planetesimal bow shocks (Hood 1998; Morris et al. 2012), but fits well with a turbulent dissipation scenario for chondrule formation. FUV and X-ray non-thermal ionization, which cannot penetrate deeply, make protoplanetary disk surface layers more magnetically active than the cold, neutral midplane (Gammie 1996), and hence good candidate chondrule formation regions. Because the high altitude chondrule forming regions would contain only a small fraction of the overall disk mass, they are also promising in that they would not be expected to process too much disk material, and could explain why chondrules are as small as they are (Hubbard & Ebel 2015). Other locations, such as radially localized zonal flows, could have also achieved the required sorting, but would have had to have been extremely strong, and would have had to have been temporally correlated with chondrule formation for the sorting to have led to chondrule-matrix partitioning.

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